Vortical and Large-Scale Structures in a Turbulent Boundary Layer

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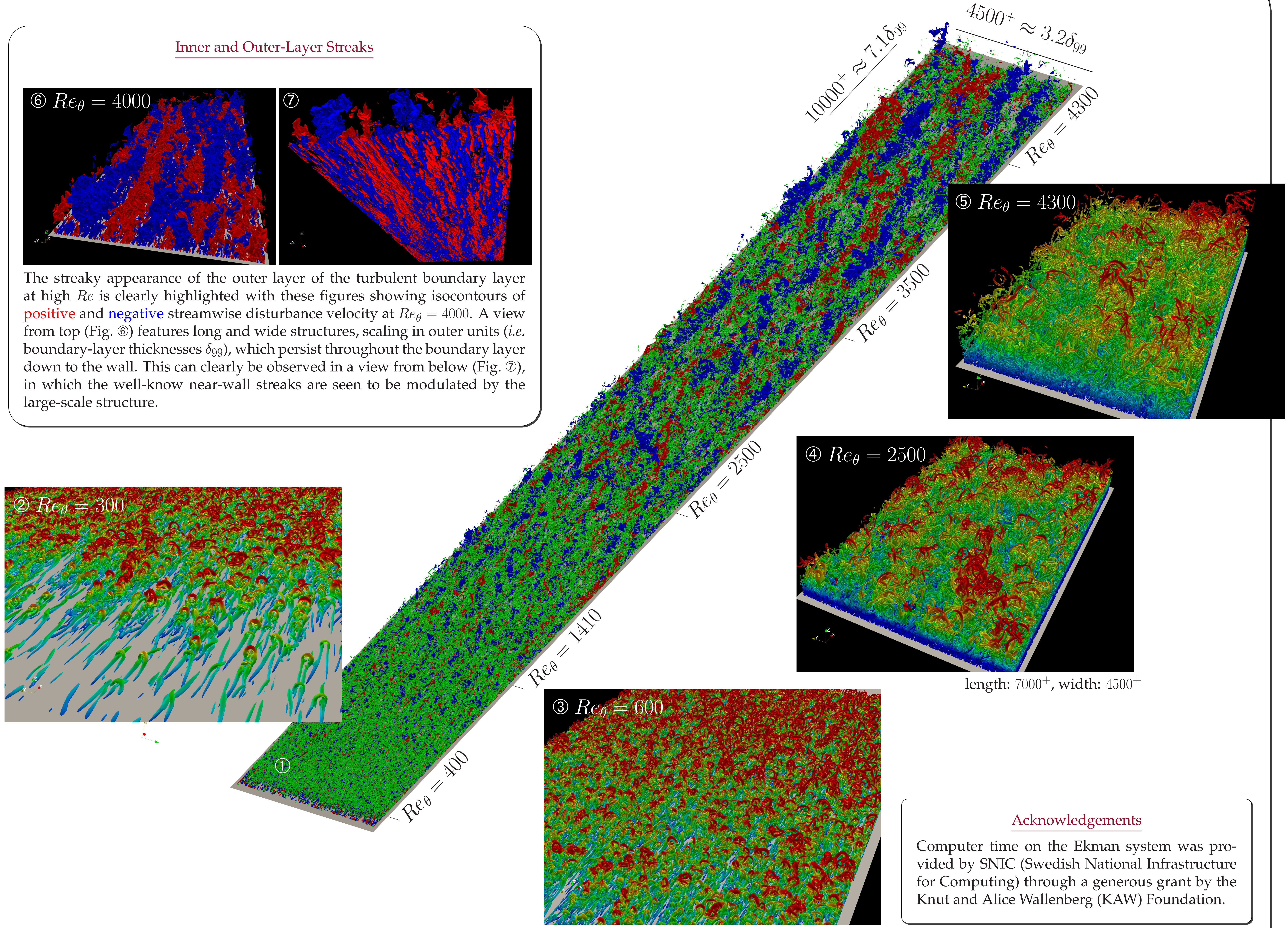
Case Description

A canonical turbulent boundary layer under zero pressure gradient is studied via direct numerical simulation (DNS). The boundary layer is spatially developing on a smooth flat plate, and transition to turbulence of the inflowing laminar Blasius boundary layer is triggered by a random volume force shortly downstream of the inflow, similar to a tripping strip in an experiment [5, 6]. The simulation covers a large domain starting at $Re_\theta = 180$ extending up to the (numerically high) $Re_\theta = 4300$ (based on the momentum thickness θ and free-stream velocity U_∞). The chosen numerical resolution for the fully spectral numerical method [2] is high enough to resolve the relevant flow structures; in the wall-parallel directions $\Delta x^+ = 9$ and $\Delta z^+ = 4$ is achieved. The whole simulation domain requires a total of $8 \cdot 10^9$ grid points in physical space. Turbulence statistics of the flow (not shown here) are in very good agreement with experimental studies at similar Reynolds numbers [5, 6].

Visualisation Results



Inner and Outer-Layer Streaks

The streaky appearance of the outer layer of the turbulent boundary layer at high Re is clearly highlighted with these figures showing isocontours of positive and negative streamwise disturbance velocity at $Re_\theta = 4000$. A view from top (Fig. ⑥) features long and wide structures, scaling in outer units (*i.e.* boundary-layer thicknesses δ_{99}), which persist throughout the boundary layer down to the wall. This can clearly be observed in a view from below (Fig. ⑦), in which the well-know near-wall streaks are seen to be modulated by the large-scale structure.

length: 7000^+, width: 4500^+

The complete turbulent boundary layer (Fig. ①) is visualised by means of isocontours of negative λ_2 [3], positive and negative streamwise disturbance velocity. The various insets highlight the different development stages of the boundary layer (isocontours of λ_2 coloured by the wall distance), accurately captured by the present numerical setup: During laminar-turbulent transition (Fig. ②), hairpin vortices dominate the span of the flow [1], with their heads being visible for some distance downstream (③). This feature of low-Re turbulent flow was recently put forward in Refs. [4] and [7], denoted as "forest of hairpins". However, as the Reynolds number is increased, the scale separation between inner and outer units is getting larger, and the flow is less and less dominated by these transitional flow structures. At $Re_\theta = 2500$, Fig. ④, isolated instances of hairpin arches can still be observed, riding on top of the emerging outer-layer streaky structures. At the highest present Reynolds number, $Re_\theta = 4300$ shown in Fig. ⑤, individual hairpins cannot be seen any longer. The boundary layer now is truly turbulent, and the outer layer is dominated by large-scale streaky organisation (see also Figs. ⑥ and ⑦) of the turbulent vortices.

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